13.3 Elementary Particles

SECTION EXPECTATIONS

- Define and describe the concepts and units related to the present-day understanding of elementary particles.
- Analyze images of the trajectories of elementary particles to determine the mass-versus-charge ratio
- Describe the standard model of elementary particles in terms of the characteristic properties of quarks, leptons, and bosons.
- Identify the quarks that form familiar particles such as the proton and the neutron.

KEY TERMS

- lepton
- hadron
- quark
- standard model

By the 1930s, scientists believed that they knew the particles on which all matter was built — the proton, the neutron, and the electron. These were the "elementary" particles, in that nothing was more basic. Nature, however, was not that simple. The first hint of a greater complexity came with the missing energy and momentum in beta decay and Pauli's proposal of the neutrino.

Today, even the proposition that these particles are massless is being challenged. Several difficulties with our understanding of the nuclear reactions in the Sun would be cleared up if neutrinos actually had mass. Neutrinos are extremely tiny and neutral, so they barely interact with matter. Consequently, during the day, neutrinos rain down through us from the Sun. At night, they pour through the planet and stream upward through us.

In 1935, Japanese physicist, Hideki Yukawa (1907–1981) proposed that the strong nuclear force that bound the nuclei together was carried by a particle with a mass between that of the electron and the proton. This particle came to be known as a "meson," because of its intermediate mass. Eventually, it was discovered in 1947, when it was termed the "π meson" (or simply, the "pion"). In fact, though, these particles are not the ones that hold the nuclei together — they never interact with other particles or nuclei by means of the strong force. Elementary particle physics is one of the most active fields in theoretical physics.

The Search for New Particles

In Section 13.2, you learned that research into beta decay revealed the existence of neutrinos and positrons. Physicists discovered that positrons were, in fact, antielectrons. When a particle (positron) and its antiparticle (electron) interact, they annihilate each other and transform into two gamma rays. With the realization that the proton, neutron, and electron were not the only subatomic particles, physicists began to search in earnest for more elementary particles.

In Chapter 8, Fields and Their Applications, you learned how electric and magnetic fields are used in powerful instruments to accelerate protons and electrons to close to the speed of light. When these extremely high-energy particles collide with other particles and nuclei, new, very short-lived particles are produced. For example, when a very high-energy proton collides with another proton, a neutral particle called a "neutral pion" (π^0) is produced. The particle exists for only about 0.8×10^{-16} s, and then decays into two gamma rays.

You are probably wondering how physicists can study a particle that disappears within 10^{-16} s after it is produced. One instrument that physicists use is called a "cloud chamber," which was invented in 1894 by C.T.R. Wilson (1869–1959). A cloud chamber contains a cold, supersaturated gas. When any form of ionizing radiation passes through, the ions formed in the path of the particle form condensation nuclei and the cold gas liquefies, creating a visible droplet. If the cloud chamber is placed in a magnetic field, charged particles will follow curved paths. Physicists analyze photographs of the "tracks" in the cloud chamber and can determine their size and speed. In the following investigation, you will make observations using a cloud chamber.

During the 1930s and 1940s, several more particles were discovered, and physicists also realized that every elementary particle has an antiparticle. U.S. physicists S.H. Neddermeyer and C. D. Anderson discovered positive and negative muons (μ^+ and μ^-) that have a mass about 207 times that of an electron. Muons have a lifetime of 2.2×10^{-6} s and decay as shown below.

$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$$
$$\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

These discoveries also revealed the existence of muon neutrinos (ν_μ) and muon antineutrinos ($\overline{\nu}_\mu$). The subscript e must now be used to indicate electron neutrinos.

In the 1940s, two more pions were discovered, one having a positive charge and the other a negative charge. These pions have a lifetime of 2.6×10^{-8} s and decay as shown below.

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Since these early discoveries, physicists have continued to identify many more extraordinary particles. Eventually, a pattern evolved and physicists were able to start classifying these elementary particles according to the types of forces through which they interact with other particles. For example, protons and neutrons interact through the strong nuclear force, whereas electrons do not experience the strong nuclear force. Particles might be affected by one or more of the four fundamental forces — gravitational, electromagnetic, strong nuclear, and weak nuclear forces.

Families of Particles

The smallest family of particles is the photon family, consisting only of the photon itself. Photons interact only through the electromagnetic force and interact only with charged particles. The photon is its own antiparticle.

The **lepton** family of particles interacts by means of the weak nuclear force. Leptons can interact through the gravitational force,